At-Sea Material Transfer

A Brief Study of Future Capabilities

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Overall Objectives

- At a fundamental level, assess the science and technology associated with material transfer in a seaway with a desire to dramatically increase capacity, operability and transfer rates in up to sea state 5 with reduced manning.

- Specifically:

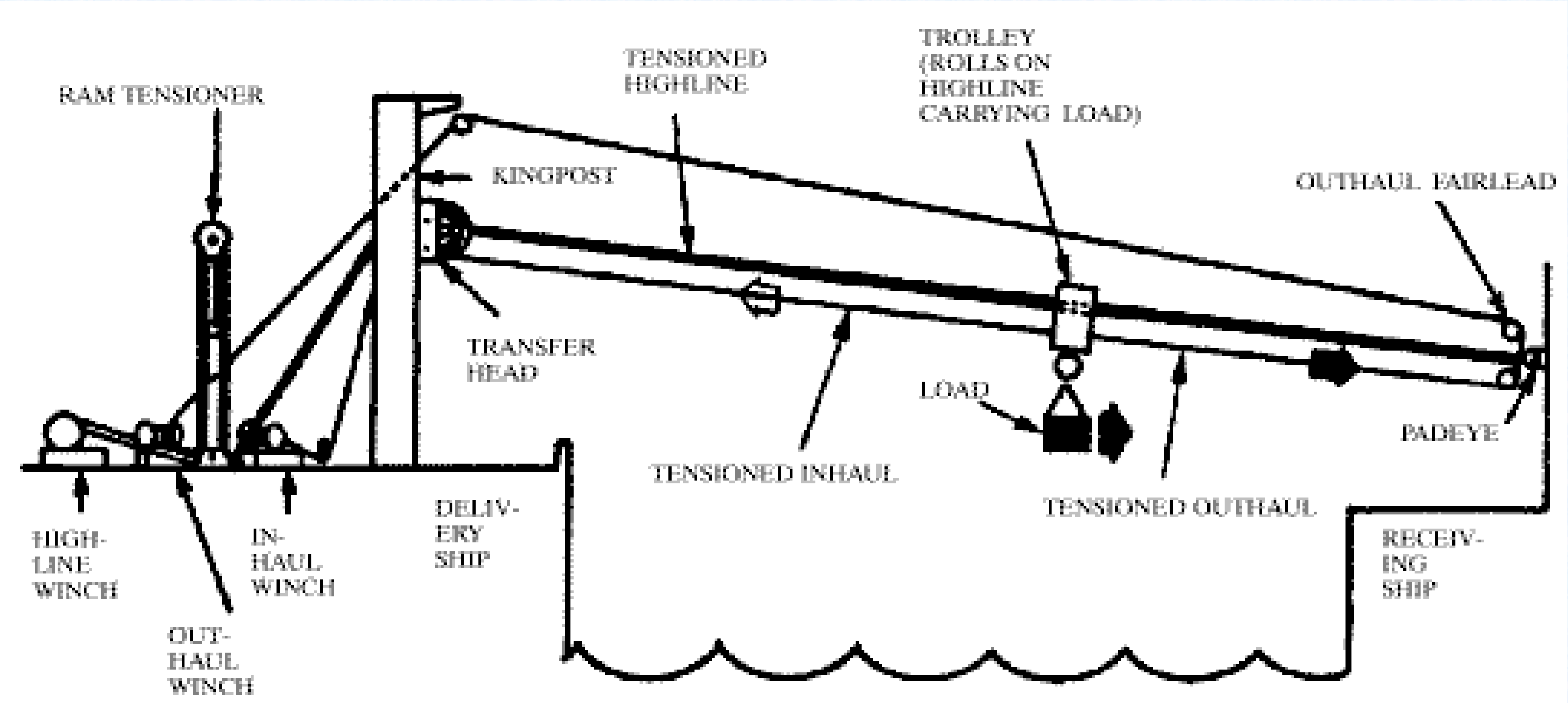
  - Heavy Underway Replenishment (UNREP)
    - Increase Capacity: 5700 to 12000 lbs.
    - Increase Ship separation: 120 to 300 feet

  - High Capacity Alongside Sea Base Sustainment (HICASS)
    - Increase Capacity 5700 to 53000 lbs.

Outline

- Underway Replenishment (UNREP)
  - Basics
  - 2D-Modeling and Simulations
  - Active control
- High Capacity Alongside Sea Base Sustainment (HiCASS)
  - Basics
  - 2D-Modeling and Simulations
  - Active control
- Technology evaluation
  - Distributed Sensing
  - Controls

UNREP Basics



Standard UNREP:

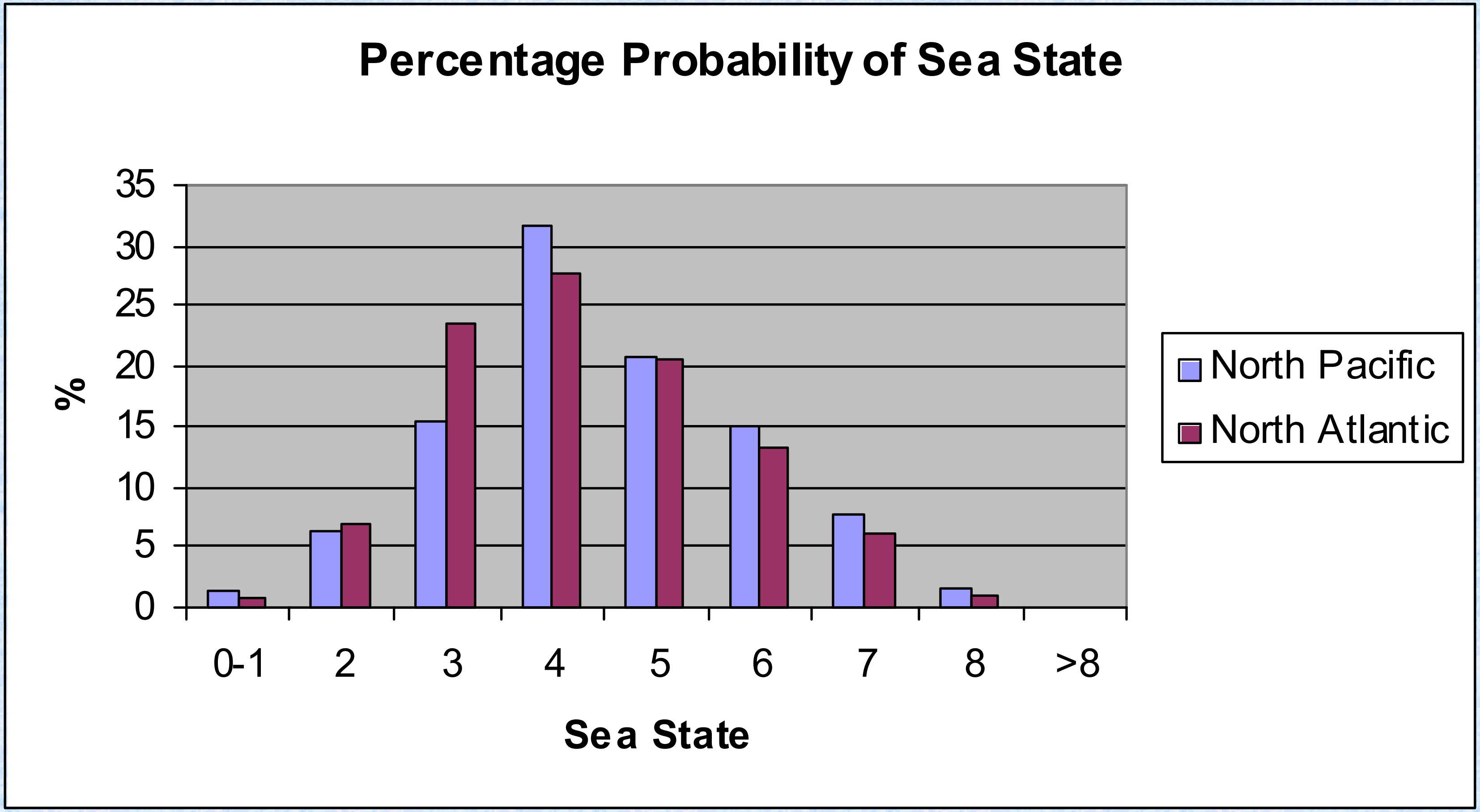
- 5700 lbs., ~120 ft. separation, up to sea state 5
- 10000 lbs, ~90 ft. separation, up to sea state 3

Heavy UNREP

- 12000 lbs, 300 ft. separation, up to sea state 5

Sea State

Principles of Naval Architecture, Vol. III, Motion in Waves



- Sea State 3 or less occurs ~25-30% of the time
- Sea State 5 or less occurs ~75-80% of the time

UNREP Dynamic Modeling

- Hydrodynamic loading/ship motion
  - Pierson-Moskowitz Model

$$S(f) = \alpha g^2 \omega^{-5} e^{\left[-1.25\left(\omega/\omega'\right)^{-4}\right]}$$

  - Response Amplitude Operator (RAO)

$$6\ DOF\ \ Motion = \sum_{i=f_1}^{f_2} A_{i,j}\sqrt{S_i}\cos\left[\left(\omega_i - \frac{\omega_i^{\,2}}{g}U\cos\chi\right)t + \delta_i + \varepsilon_j + kD\sin\chi\right]$$

- UNREP transfer dynamics
  - Highline
  - Inhaul/outhaul lines
  - Trolley linkage

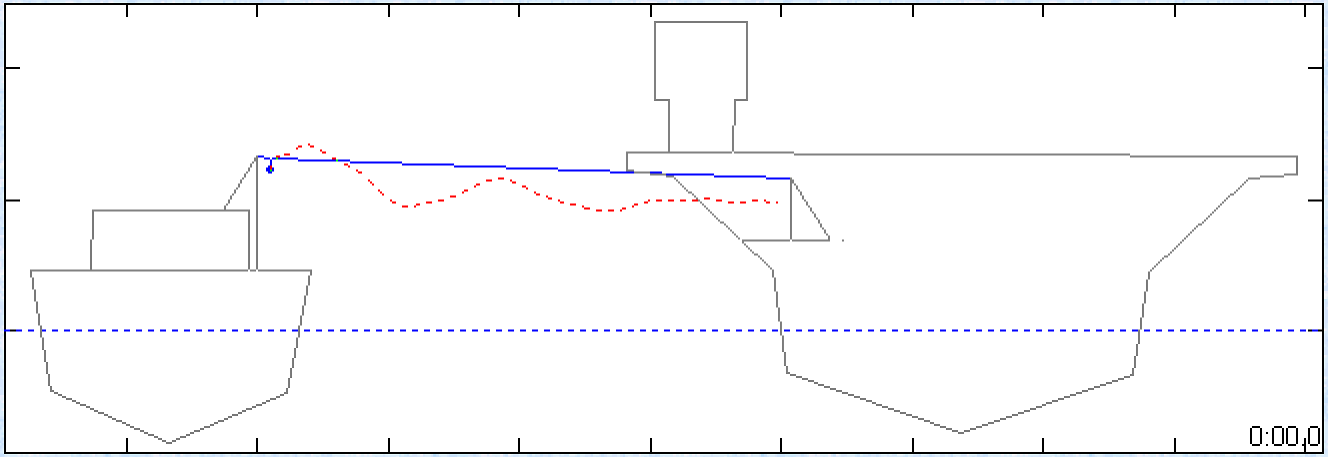
UNREP Simulation Matrix

- RAOs Generated:
  - (2) Ship configurations: AOE-CVN, AOE-DDG
  - (2) Headings (seakeeping): 180, 150 Deg.
    (0,30 deg. ship heading)
  - (3) Separation distances: ~120, ~210, ~300 feet
  - (1) Ship speed: 14.5 knots
- Transfer Loads:
  - (2) 5700, 12000 lbs.
- Sea Condition
  - (4) Sea States 0, 3, 4, 5
- Total of 96 configurations (plus control on)

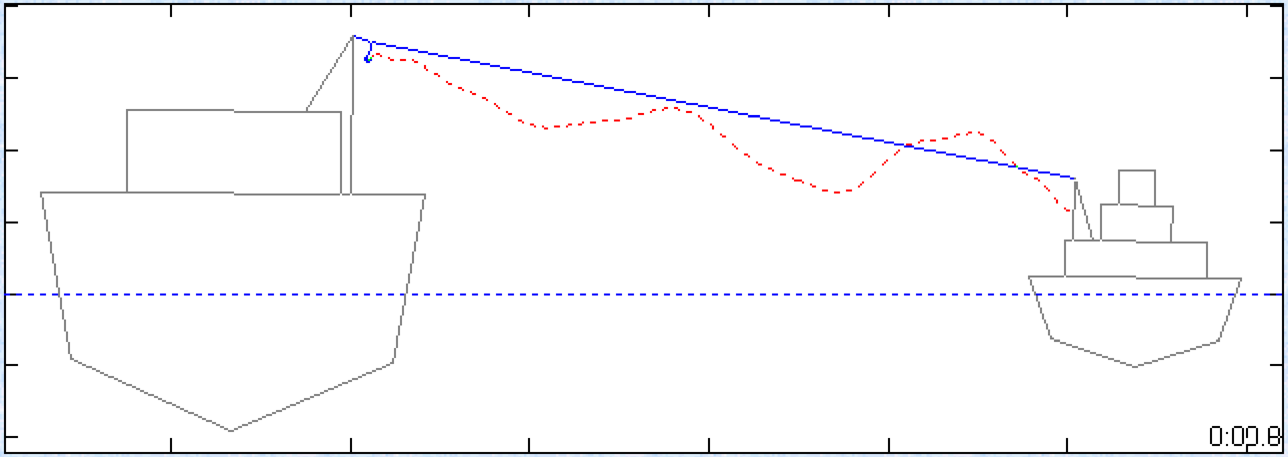
Baseline UNREP Simulations

Transfer: Sea State 5 at 120’ separate and 5700 lb Load

AOE-CVN



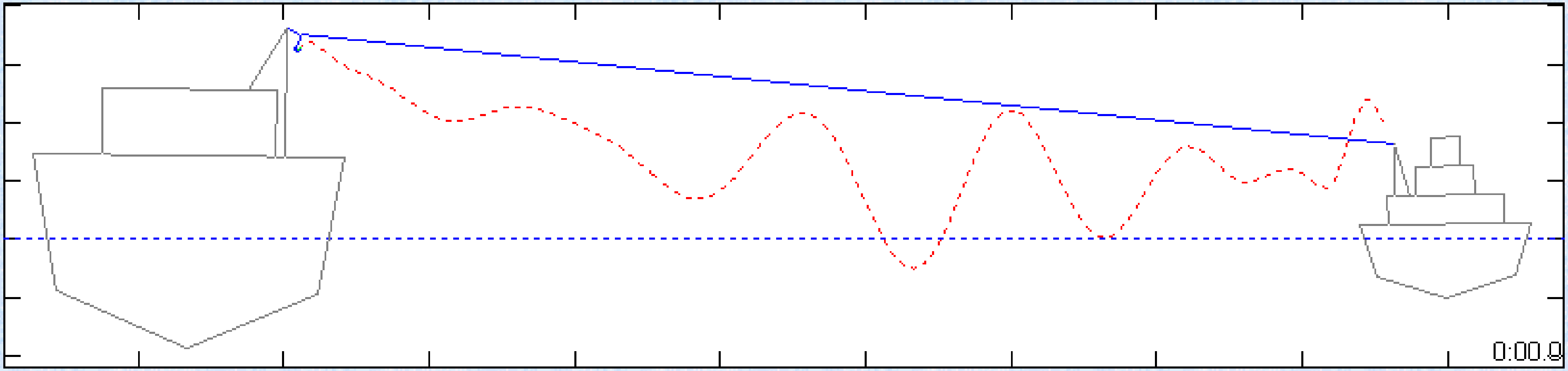
AOE-DDG



Baseline UNREP Simulations

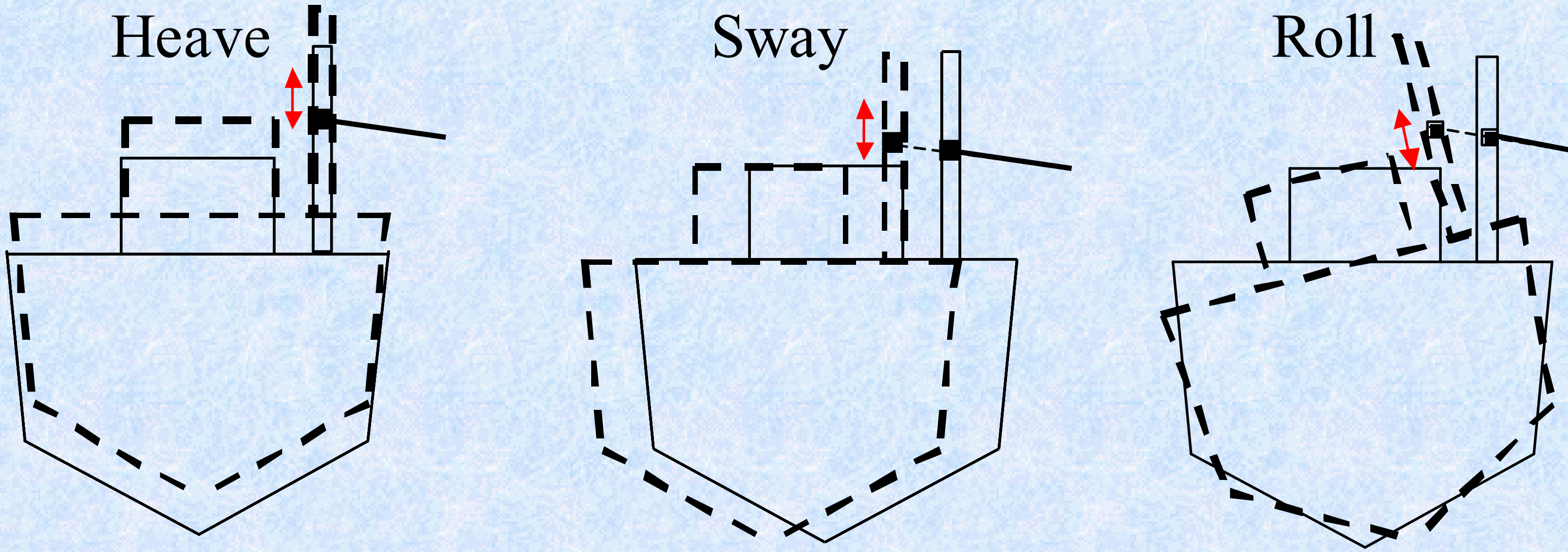
Transfer AOE-DDG with 12000 lb Load in Sea State 5

300 Foot Separation



2D Active Control Laws

- Compensate for ship motions (heave, sway and roll) by maintaining the cable line angles. This is achieved by moving attachment point up and down the kingpost.

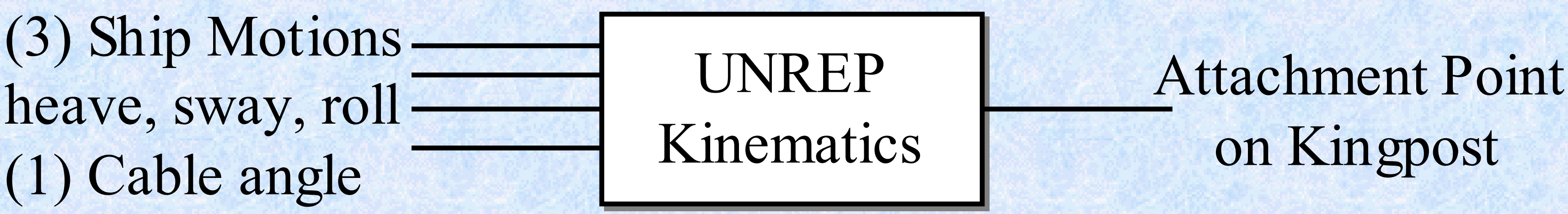


- Assume: - constant highline tension (40000 lbf)
  - constant transfer rate (10 ft/s)
  - small control system delays (Feedforward)

2D Feedforward diagram

Supply Ship

Receiving Ship

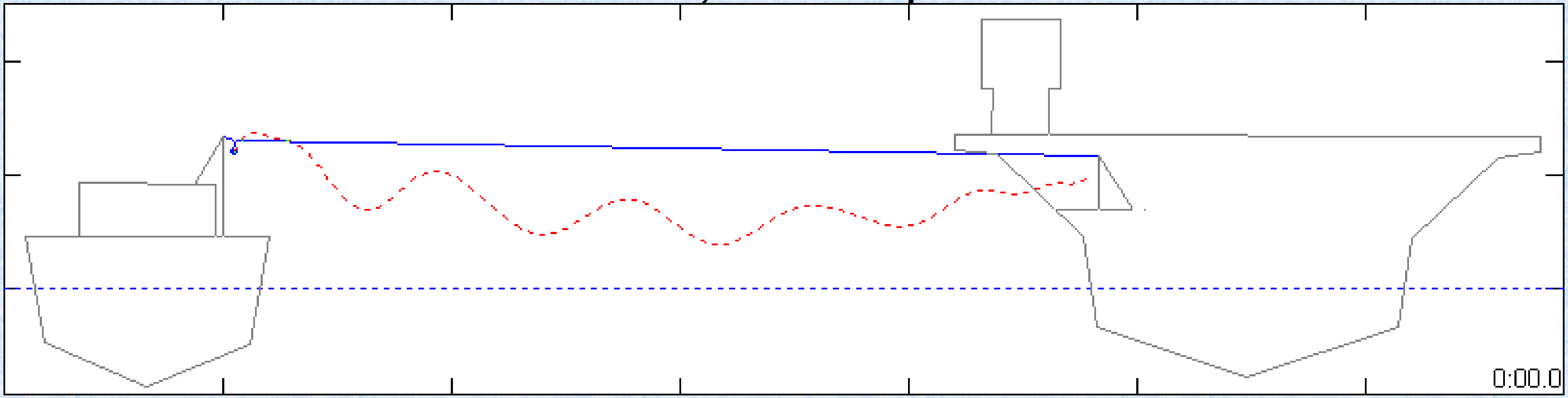


- Minimum of (4) sensors required on supply ship
- Minimum of (4) sensors required on receiving ship
- Two independent MISO (4 input – 1 output)

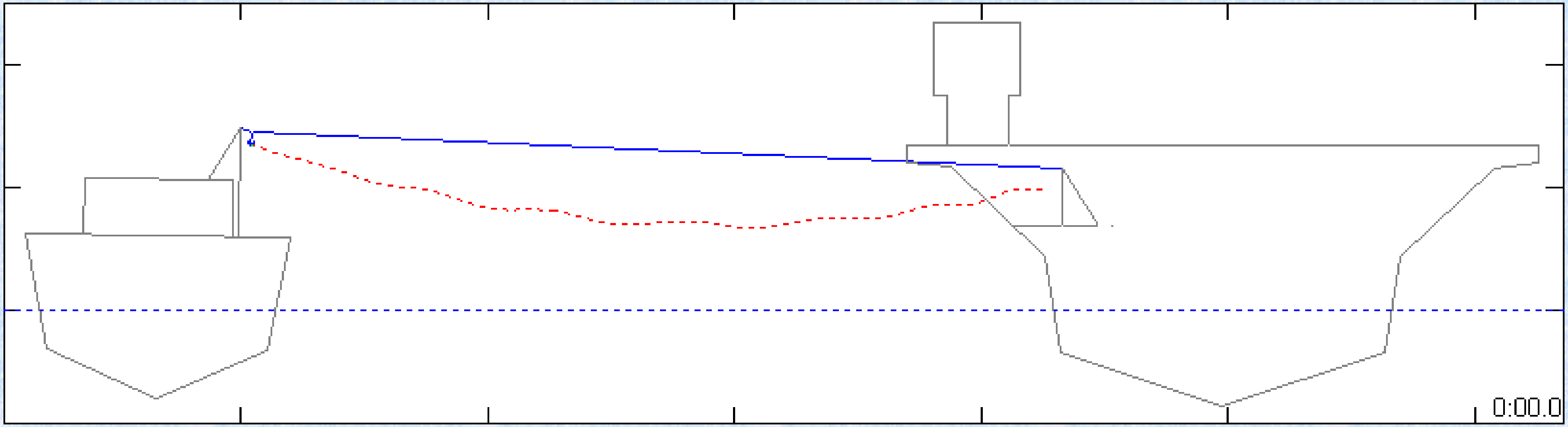
Control UNREP Simulations

Transfer AOE-CVN with 12000 lb Load in Sea State 5

No Control, 300' separation



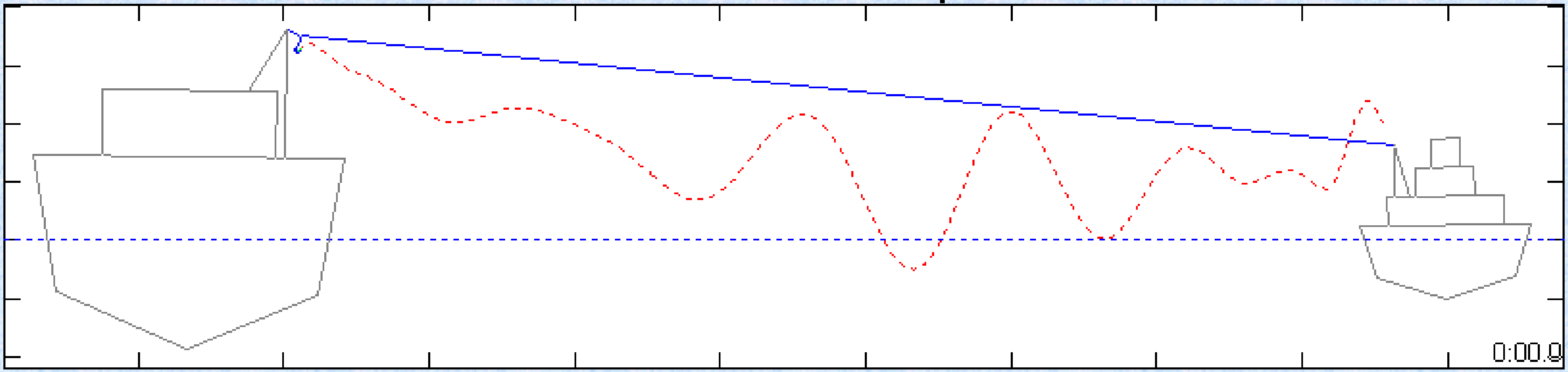
Control, 300' separation



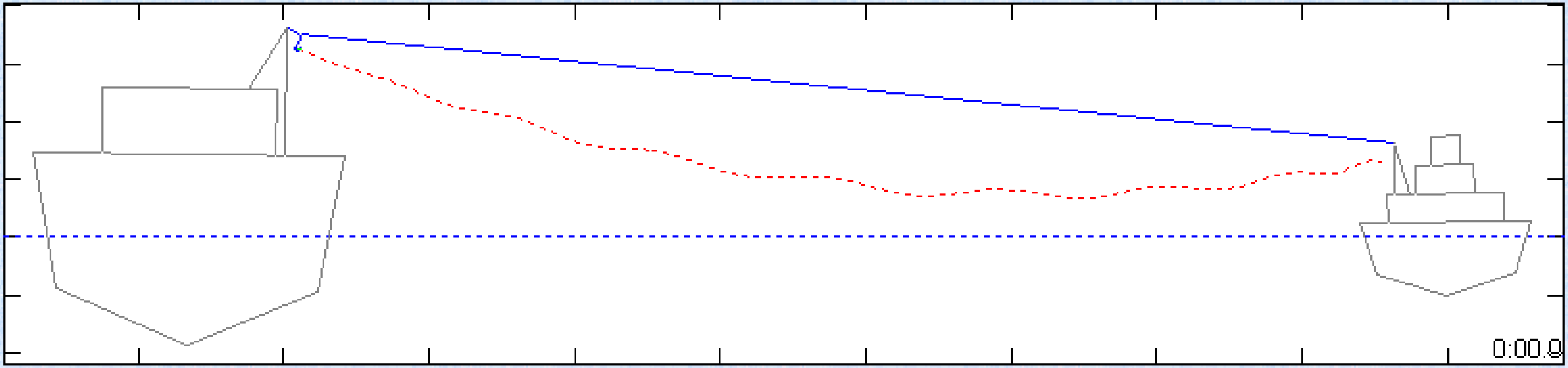
Control UNREP Simulations

Transfer AOE-DDG with 12000 lb Load in Sea State 5

No Control, 300’ separation



Control, 300’ separation

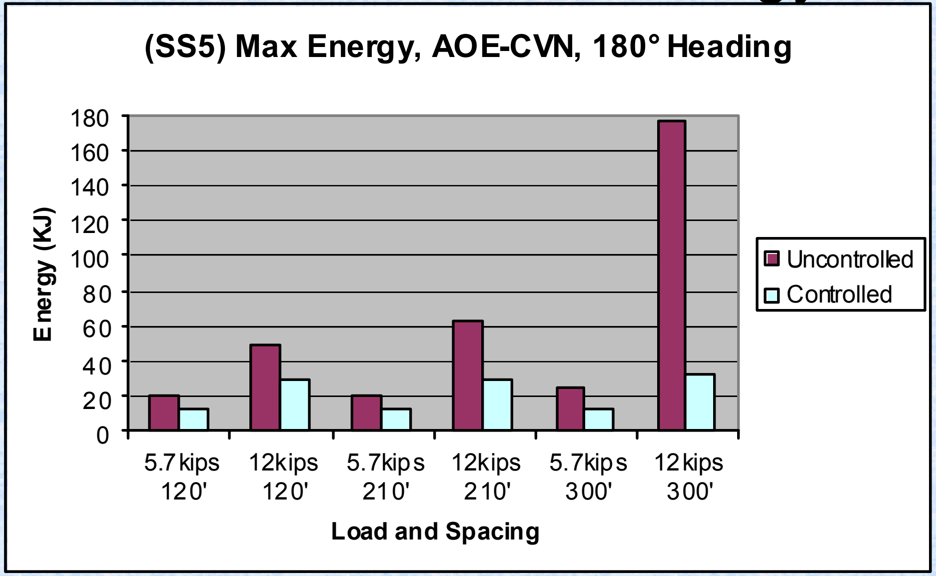


Control Simulation Results

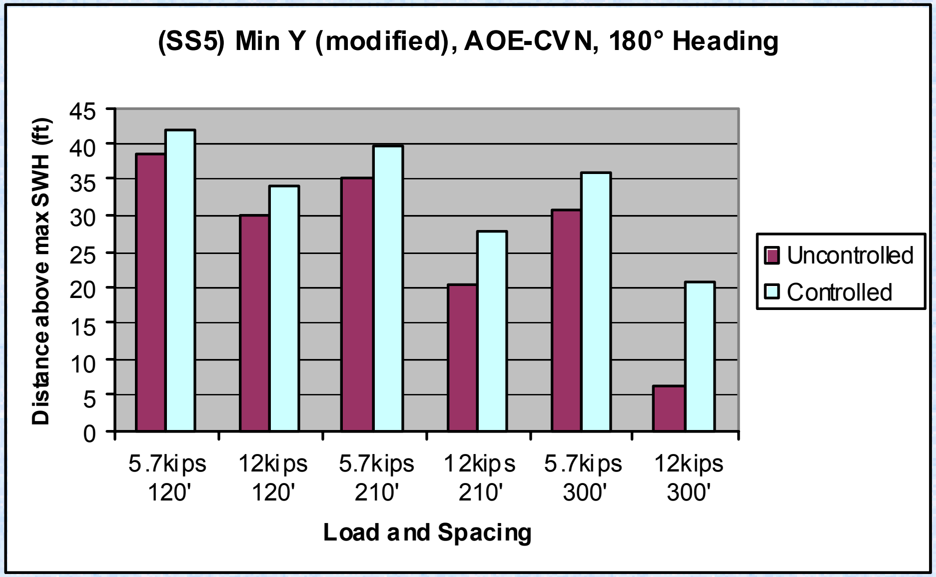
Transfer AOE-CVN in Sea State 5

Uncontrolled — Controlled

Maximum Kinetic Energy



Distance Above Water

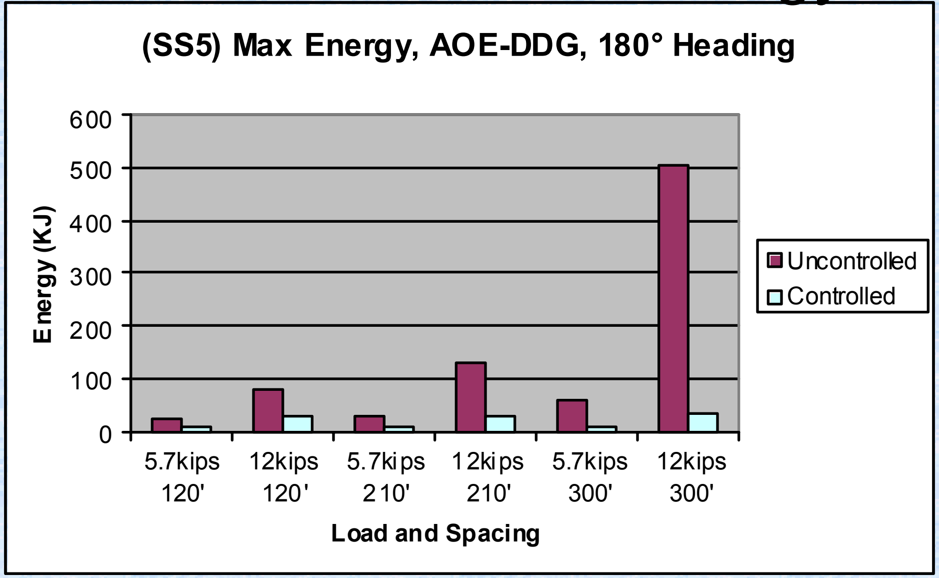


Control Simulation Results

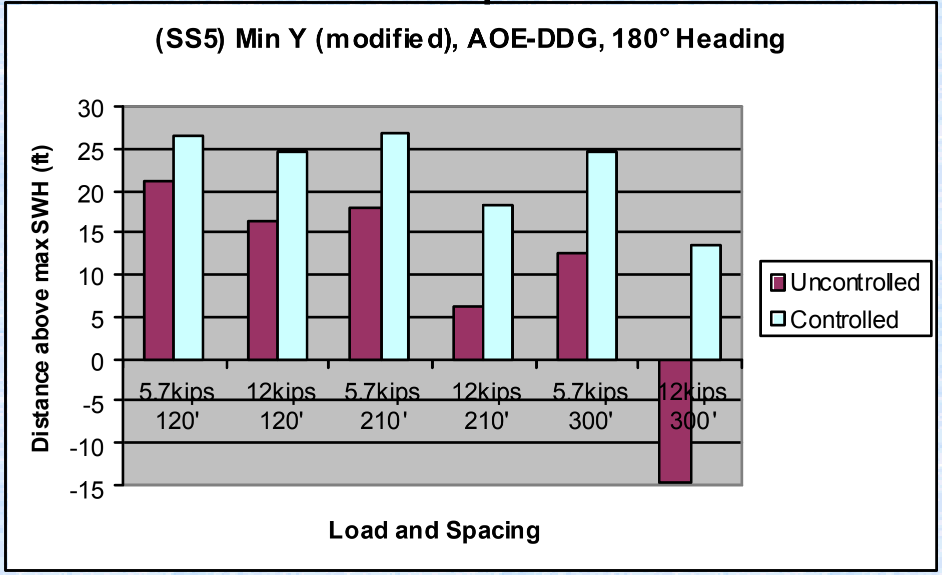
Transfer AOE-DDG in Sea State 5

Uncontrolled Controlled

Maximum Kinetic Energy



Vertical Displacement



Actuators/Sensors

- Delay
  - Total delay < 140 ms
  - Actuator/sensor response may be ~100's of ms.
- Required actuator slew rates from these simulations
  - AOE - 8.5 ft/s, CVN - 4.2 ft/s, DDG - 12.4 ft/s
- Required actuator stroke (travel on kingpost)
  - AOE - 20.6 ft., CVN – 9.5 ft., DDG – 25.0 ft.
- Actuator force requirement on the order of ~50000 lbf
- 6 DOF sensing requirements for full 3D system:
  - Supply ship: (6) ship motions (6 DOF), (2) cable angles
  - Receive ship: (6) ship motions (6 DOF), (2) cable angles
- Simulator does not interconnect the sensor information between ships. In real systems with delays, full inter-connectivity may be necessary.

Critical Issues (UNREP)

- System delay (latency) < ~140ms
- May require ship motion predictive capability integrated with off-ship distributed sensing
- Actuator requirements may not be attainable
  - Overall stroke requirement of 25 feet (DDG)
  - Overall slew rate of 12 ft/s (DDG)
  - Force capacity ~50000 lbf
- Improved strength of materials with advance rope technology and Imbedded sensors for real time monitoring

Outline

- Underway Replenishment (UNREP)
    - Basics
    - 2D-Modeling and Simulations
    - Active control
- High Capacity Alongside Sea Base Sustainment (HiCASS)
    - Basics
    - 2D-Modeling and Simulations
    - Active control
- Technology evaluation
    - Distributed Sensing
    - Controls

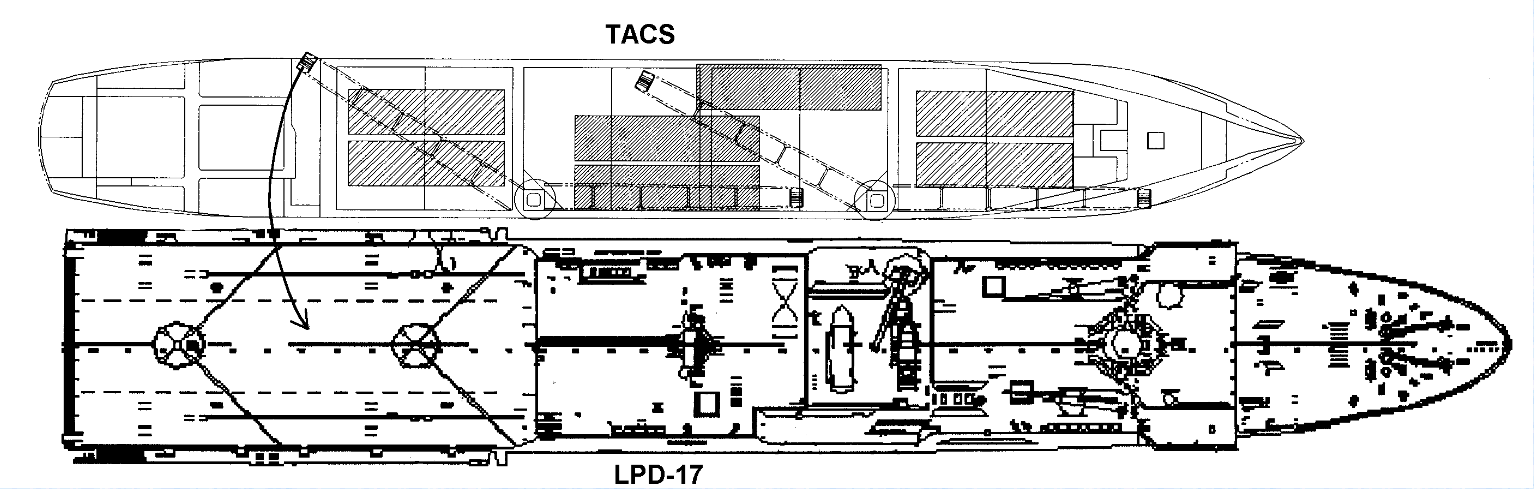
HiCASS Basics

- Ships in close proximity (10-50 feet)
- Use of crane to transfer loads up to 53000 lbs.
- Transfers in up to sea state 5
- Increase transfer rates
- Reduced manpower
- May include sea basing, fendering

HiCASS Dynamic Modeling

- Hydrodynamic loading/ship motion
  - Pierson-Moskowitz Model
  - Response Amplitude Operator (RAO)

- HiCASS transfer dynamics
  - Crane



HiCASS Control Stages

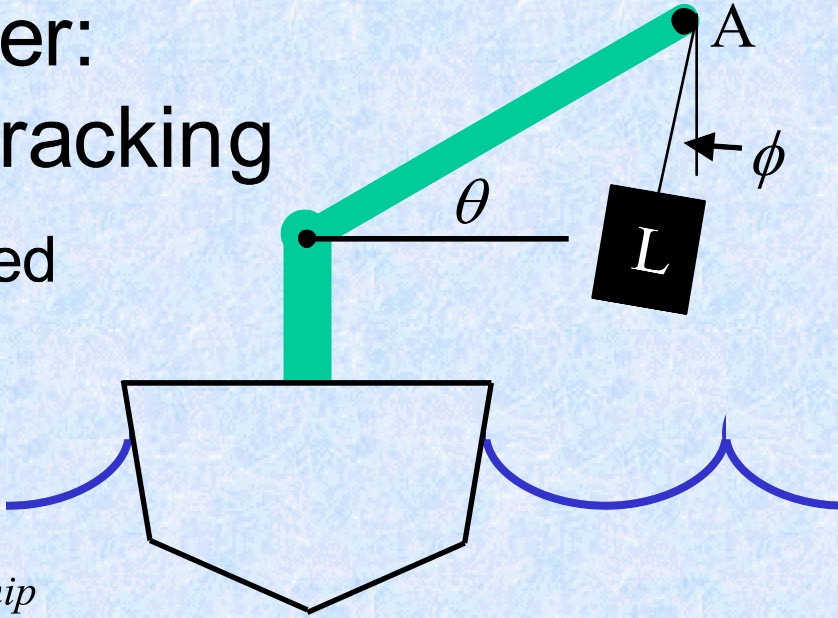
- Maintaining Position: Compensate for ship motion by controlling the crane tip.

- Horizontal Transfer (Control Laws)
  - No control: Transfer from point A to point B without ship motion or pendulation compensation
  - Partial control: Compensate for ship motion, but not pendulation.
  - Full control: Compensate for both ship motion and pendulation.

- Track receiving ship for load drop.

Active Control Laws

Horizontal Transfer: Acceleration Profile Tracking



In all cases, $\ddot{\theta}$ is controlled to give desired $\ddot{x}_A$

<u>No Control (No Compensation)</u>

Desired $\ddot{x}_{A/ship} = A_1 \Delta x_{A/ship} - A_2 \dot{x}_{A/ship}$

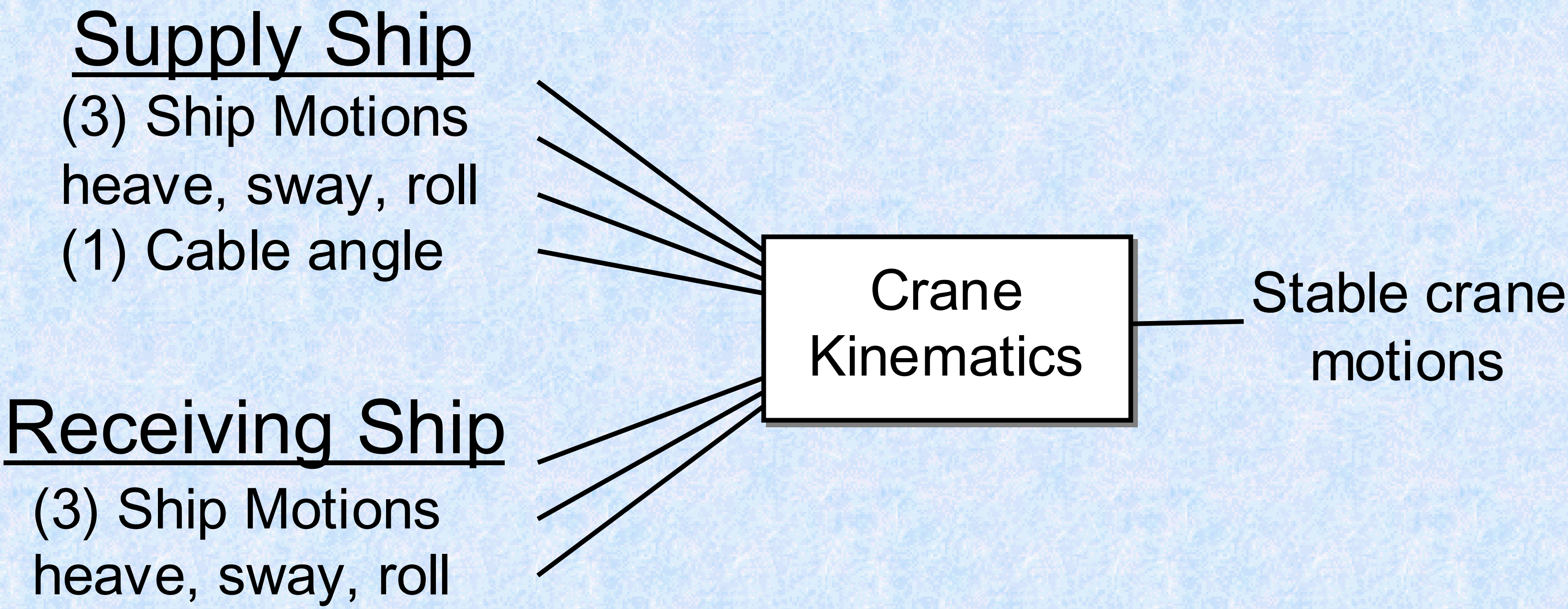
<u>Partial Control (Ship Motion Compensation)</u>

Desired $\ddot{x}_A = A_1 \Delta x_A - A_2 \dot{x}_A \qquad x_A = f\left(x_{A/ship}, ship\ motion\right)$

<u>Full Control (Ship Motion and Pendulation Compensation</u>

Desired $\ddot{x}_A = A_1 \Delta x_L - A_2 \dot{x}_L - g \sin\phi - A_3 \dot{\phi} \qquad x_L = f\left(x_A, \phi\right)$

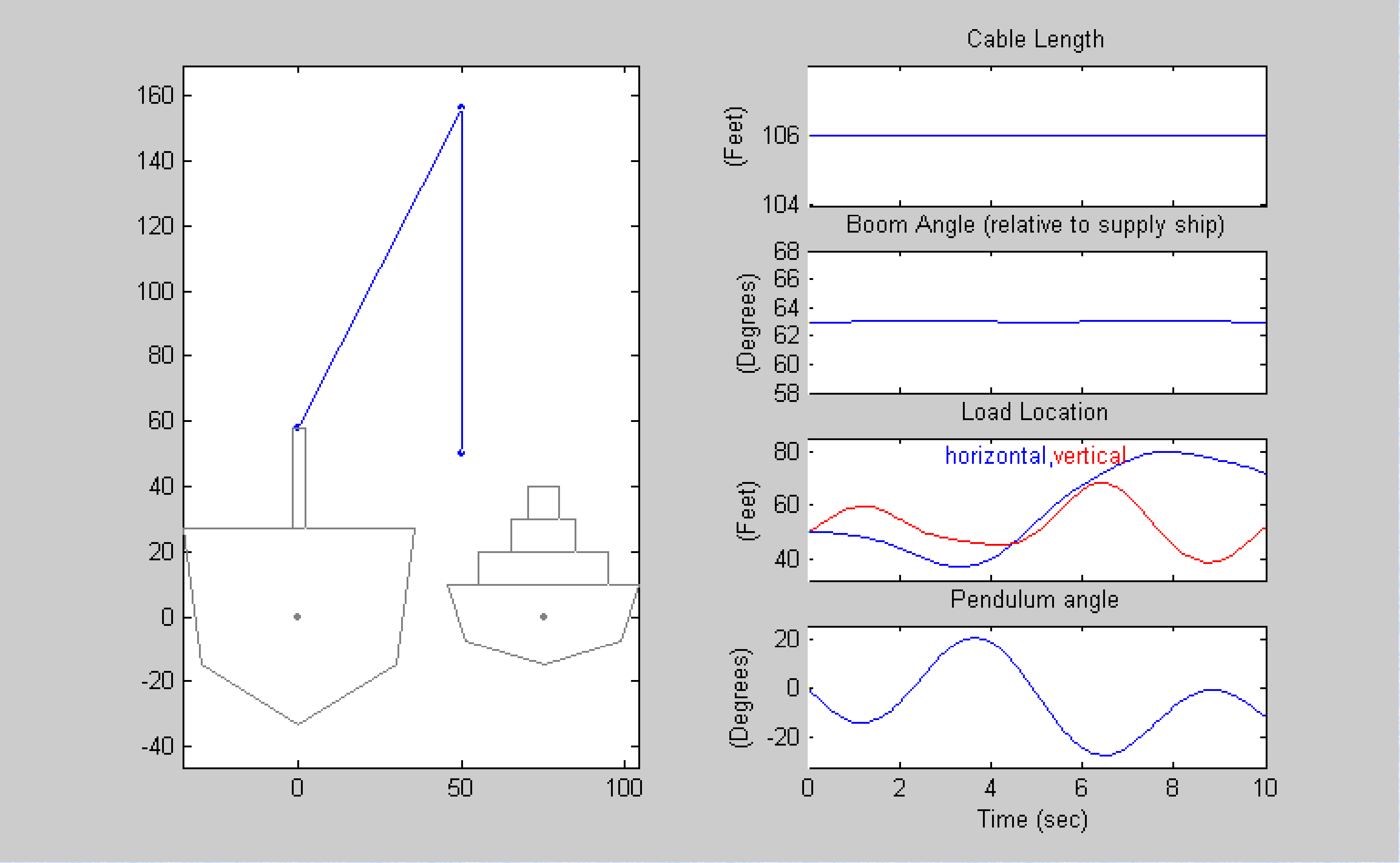
2D Feedforward block diagram



- (4) sensors required on supply ship
- (3) sensors required on receiving ship
- Fully interconnected MISO (7 inputs – 1 output)

HiCASS Simulations

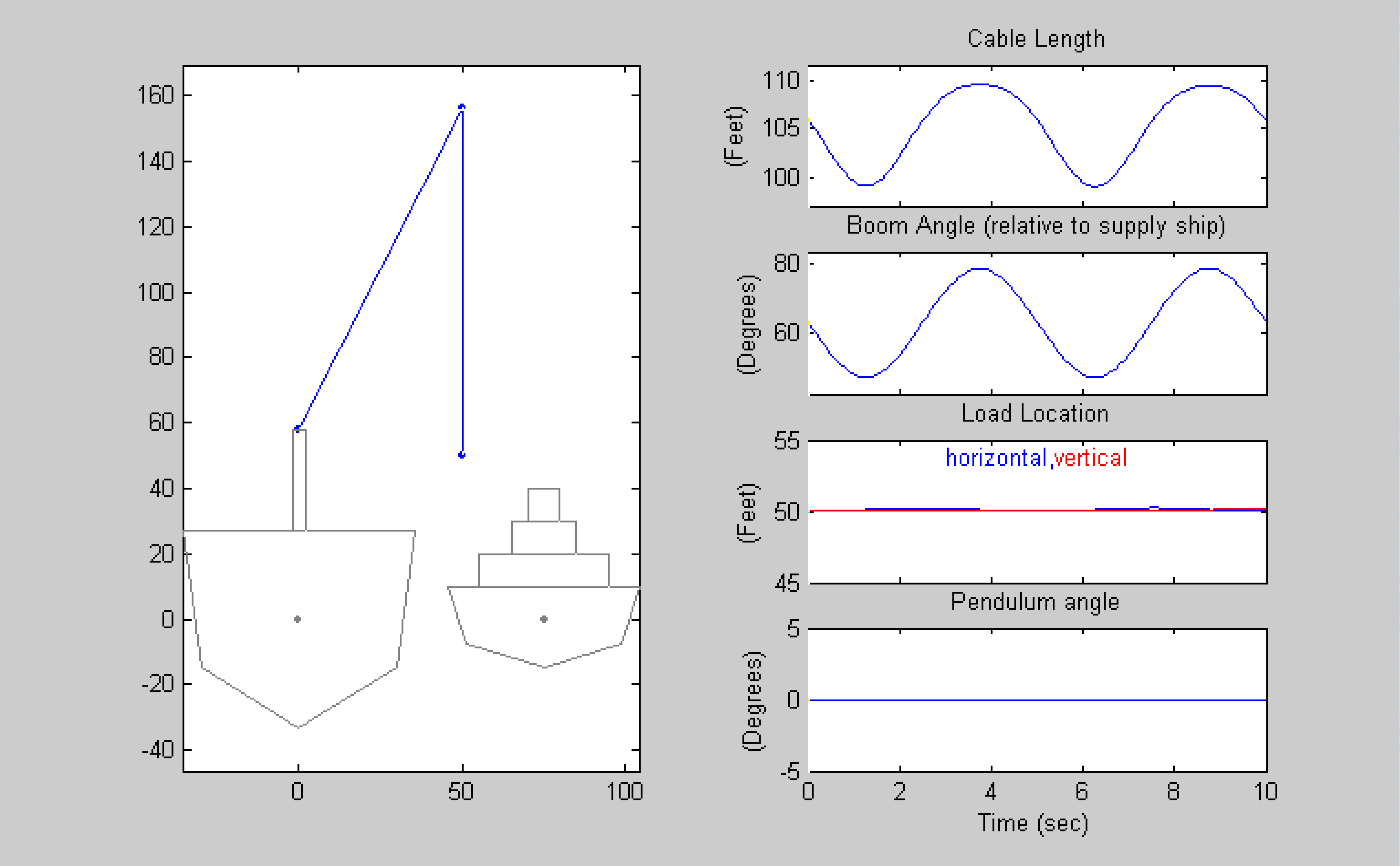
No Control, 10° Roll Simulation



- ~ 15 feet separation

HiCASS Simulations

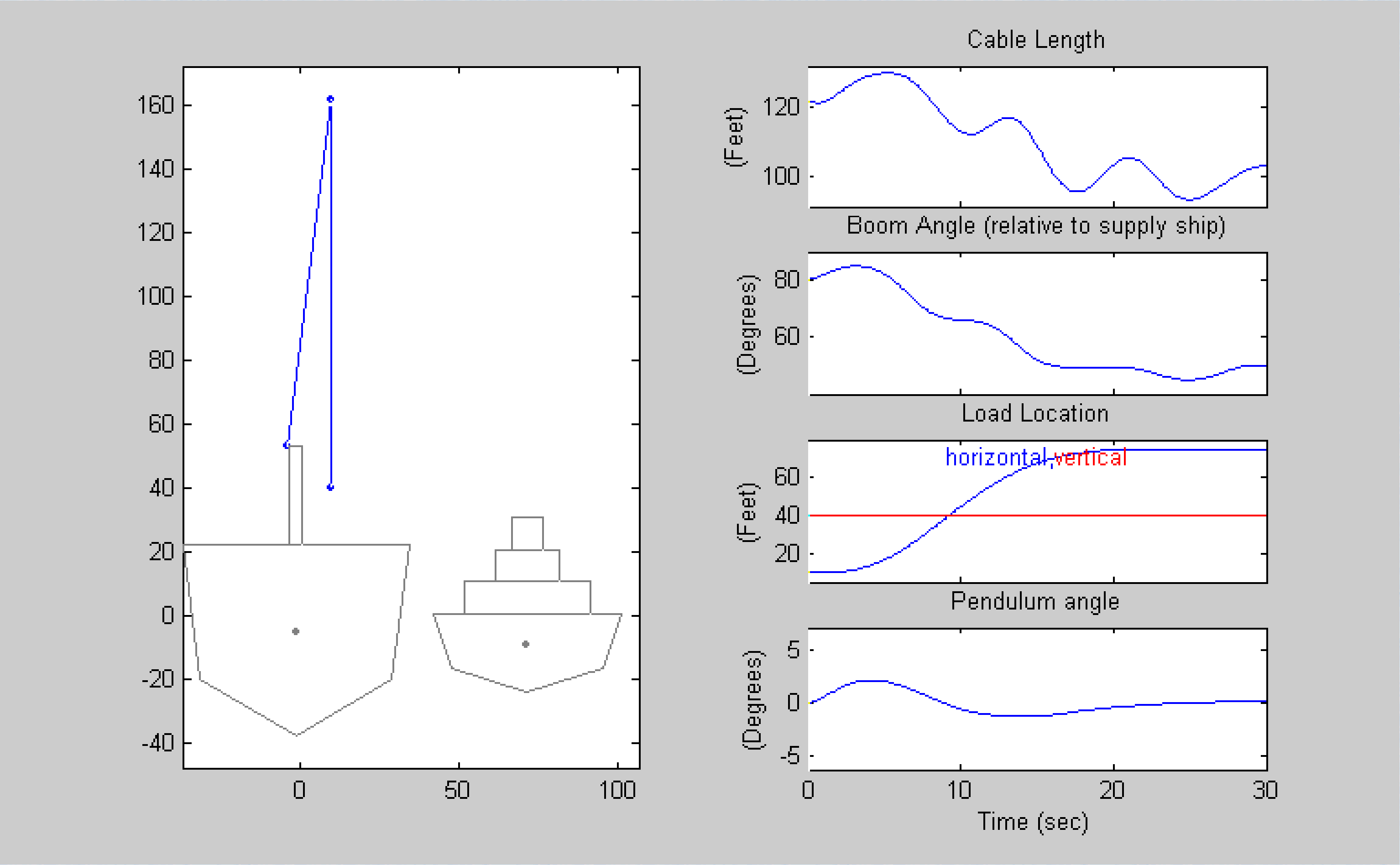
Partial Control, Control, Roll Simulation



- ~ 15 feet separation

HiCASS Simulations

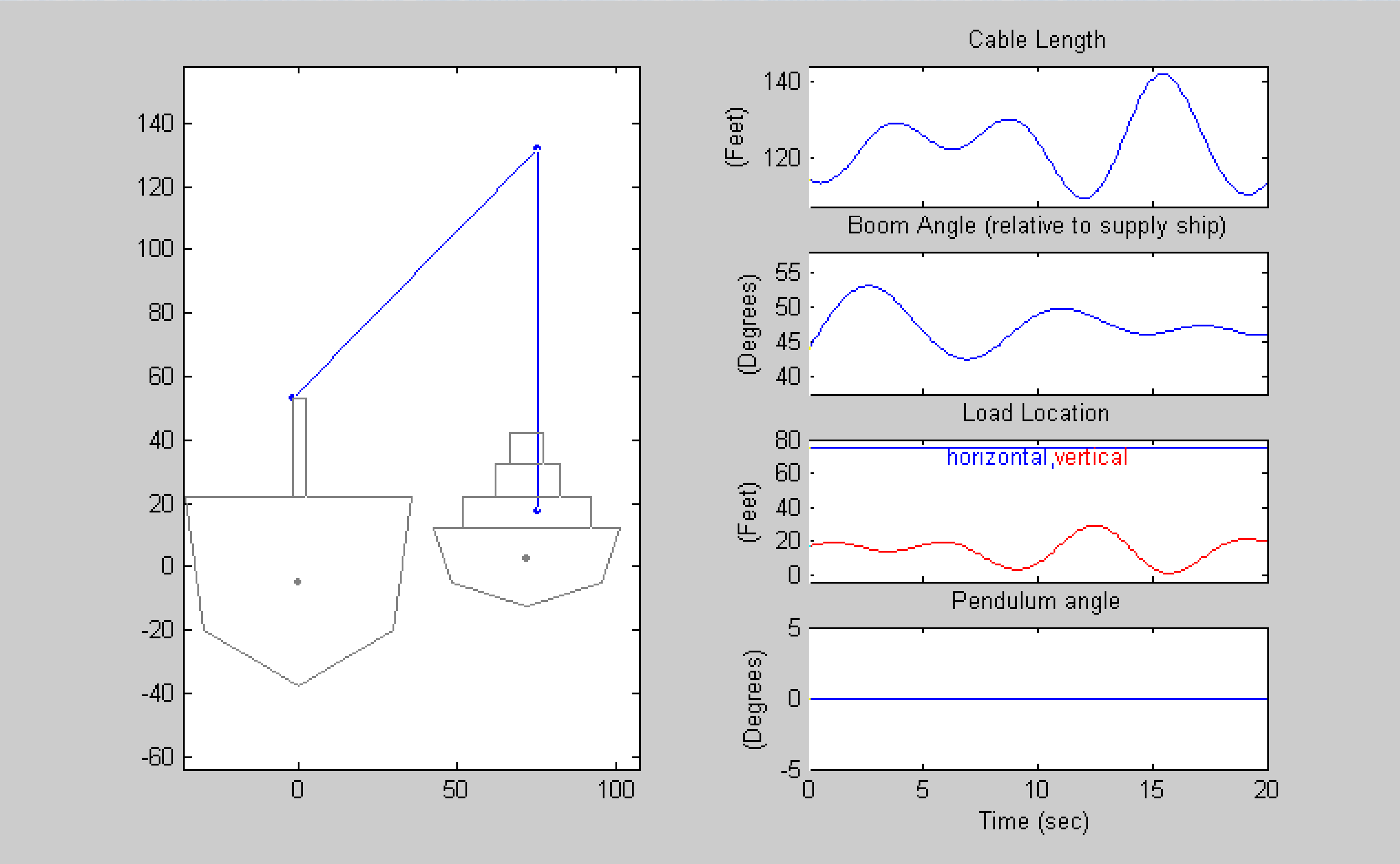
Horizontal Transfer: “Full Control” (Sea State 5)



- ~ 15 feet separation

HiCASS Simulations

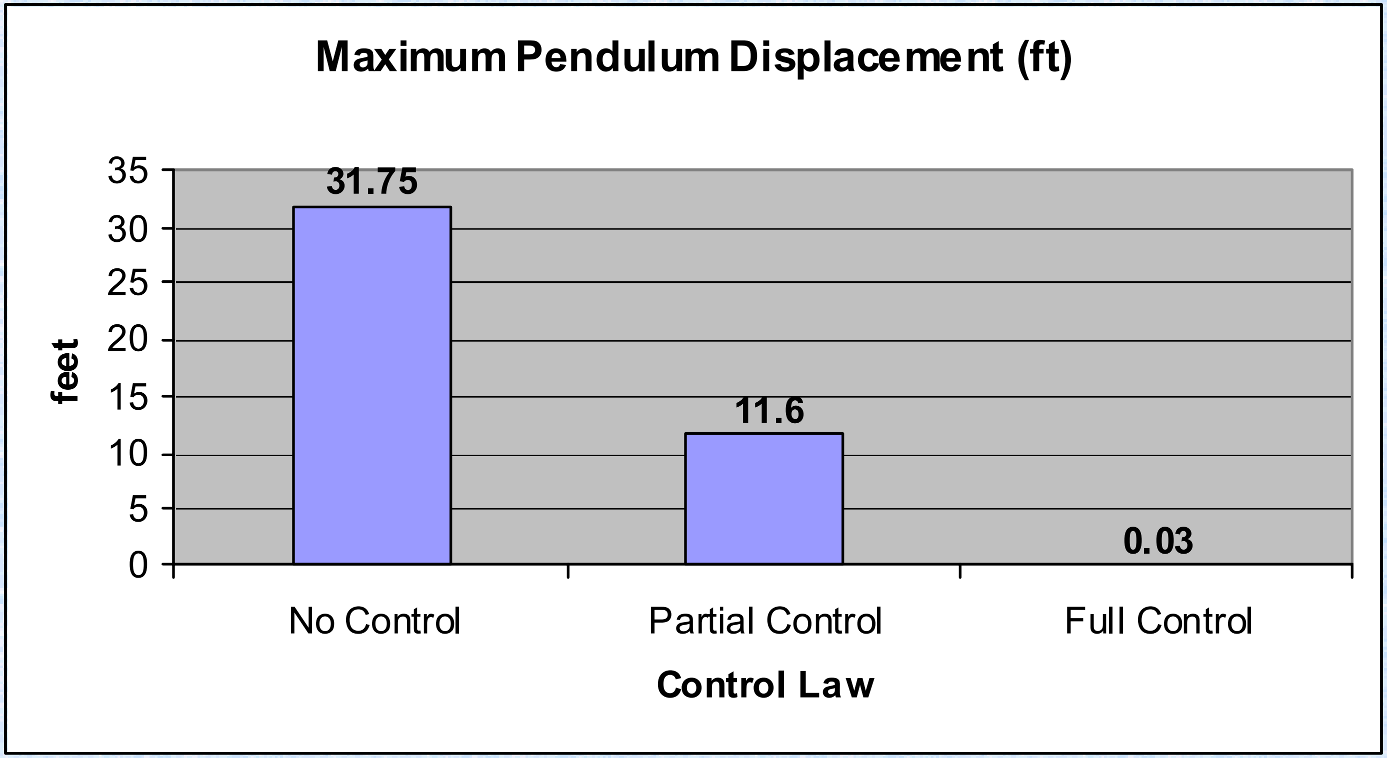
Tracking receiving ship (Sea State 5)



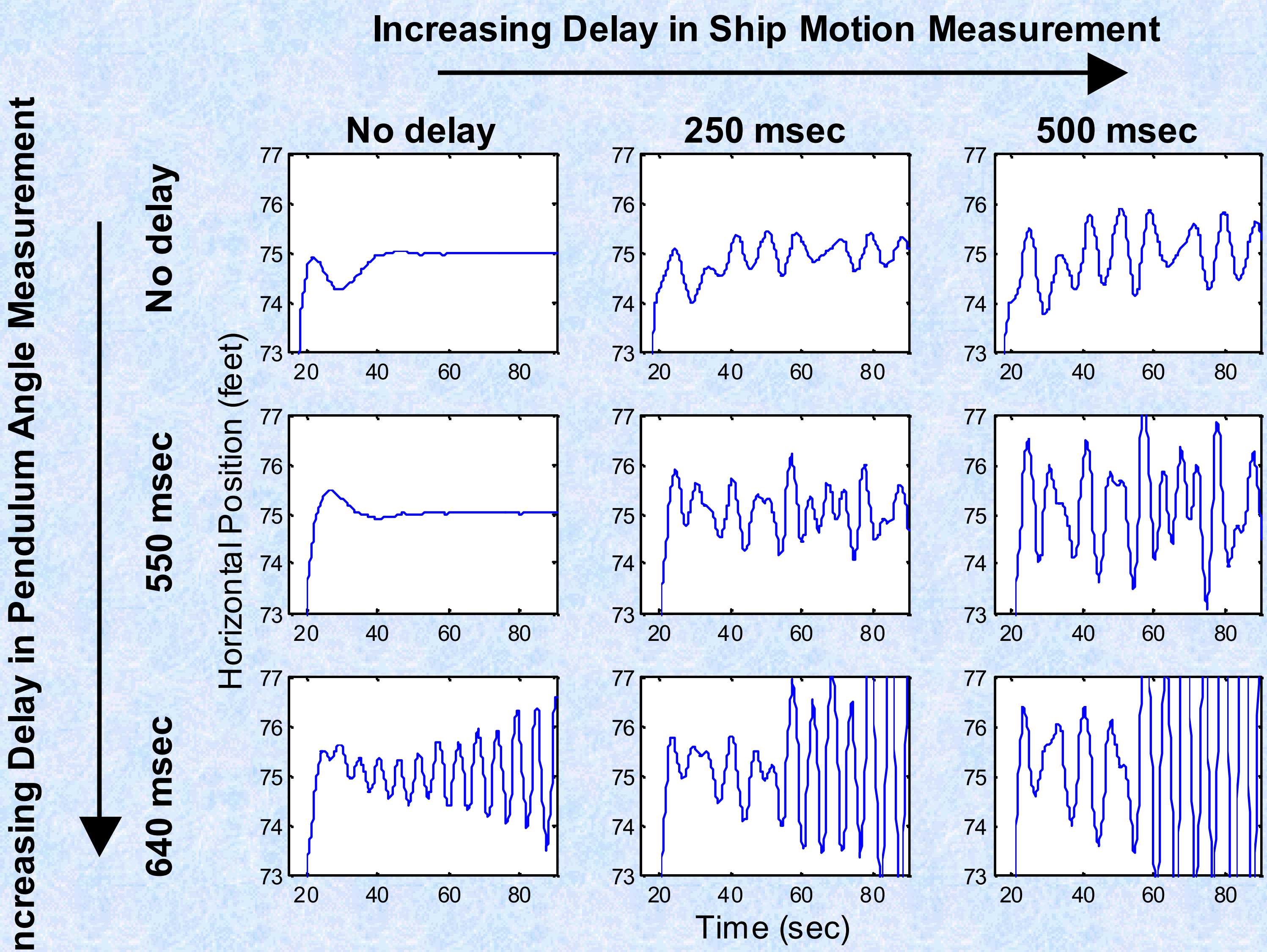
- ~ 15 feet separation, assume ship center drop

HiCASS Simulation Results

Sea State 5 Material Transfer



HiCASS Delay Study



Actuators/Sensors

- Delay:
  - Total delay < 140 ms
  - Actuator/sensor response may be ~100's of ms.
- Required actuator slew rates from these simulations
  - Cable length: ~5.0 ft/s, Boom angle: ~3 deg/s
- Force requirement for control appears to be less than that necessary for for basic motion.
- 6 DOF sensing requirements for 3D system:
  - Supply ship: (6) ship motions (6 DOF), (2) Pendulum angles
  - Receiving ship: (6) ship motions (6 DOF)
- Sensor systems fully interconnected between ships.

Critical Issues (HiCASS)

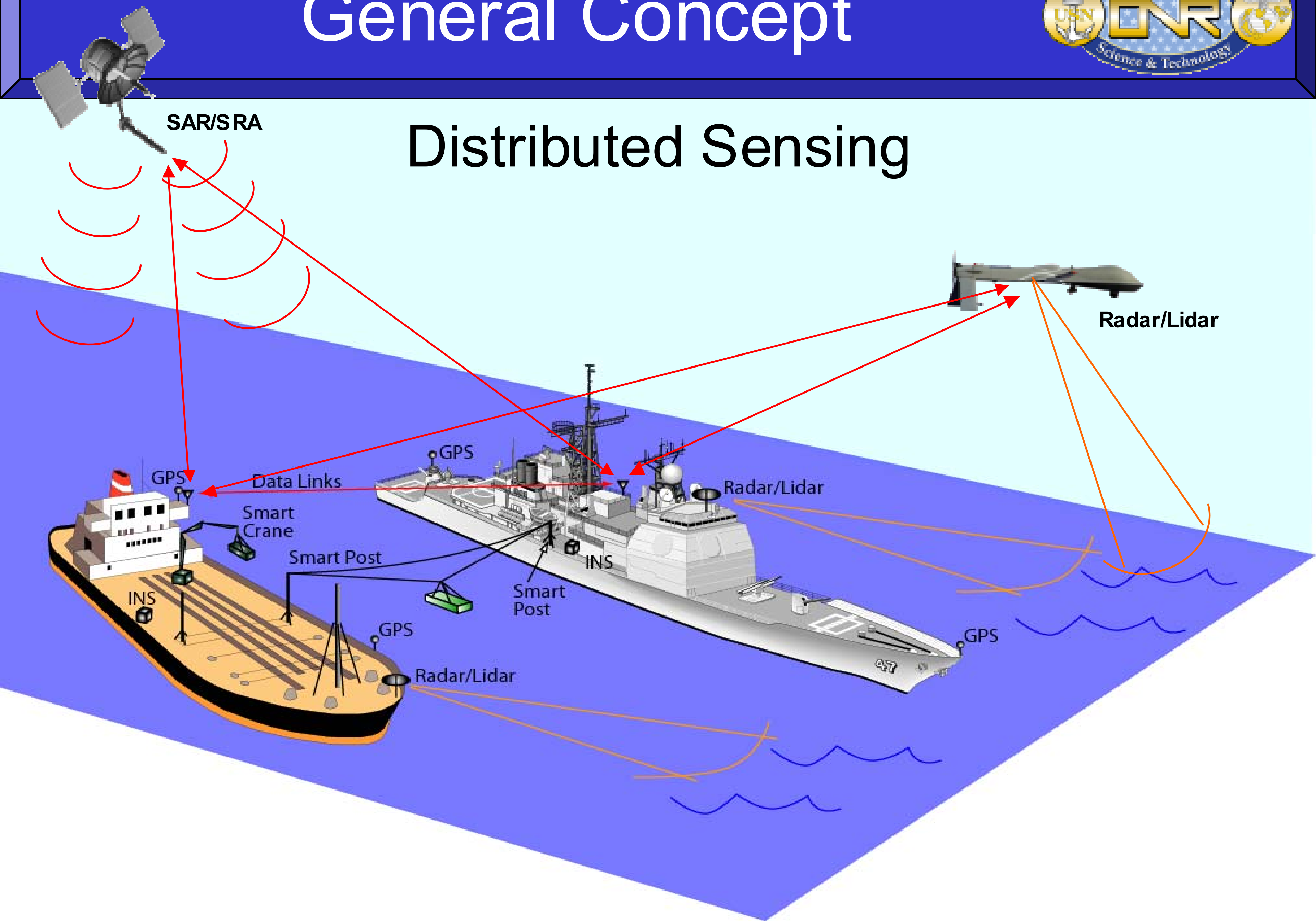
- Full interconnect (Inter-ship) control
- System delay (latency) < ~140ms (similar to UNREP)
- May require ship motion predictive capability integrated with off-ship distributed sensing
- Actuator requirements may not be attainable
  - Overall slew rate of 3 degree/s
  - Force capacity not critical
- Strength of materials: Crane, wirerope
- Steps to prevent collisions: Fendering, real-time sensing of the distance between ships

Outline

- Underway Replenishment (UNREP)
  - Basics
  - 2D-Modeling and Simulations
  - Active control
- High Capacity Alongside Sea Base Sustainment (HiCASS)
  - Definition
  - 2D-Modeling and Simulations
  - Active control
- Technology evaluation
  - Distributed Sensing
  - Controls

General Concept

Distributed Sensing



Summary

- 2D Heavy UNREP dynamic analysis shows that by controlling the highline cable angle via the vertical attachment point on the kingpost can significantly improve load stability. Especially at 300 ft. separation and sea state 5 with increased loads.
- 2D HiCASS dynamic analysis shows that crane load oscillations can be significantly reduced by using active control that compensates for both the ship motions and pendulation.
- Sensing for the active control system may require a ship motion predictive capability integrated with off-ship distributed sensing. More research is required to access this requirement as related to active control system delays (latency).
- Other critical issues involve actuator stroke, slew rate, force capacity, etc., and strength of materials associated integrations with wirerope (UNREP) and transfer crane (HiCASS) systems.